Quirky Collider Signatures of Folded Supersymmetry

Zackaria Chacko

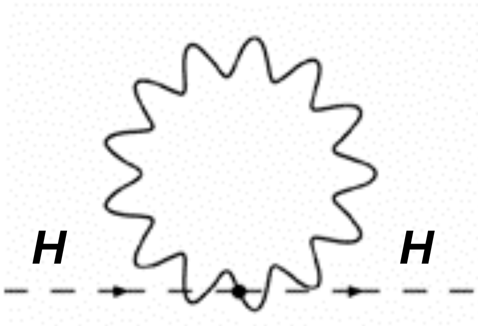
University of Maryland, College Park

ZC, Burdman, Goh & Harnik
ZC, Burdman, Goh, Harnik & Krenke

INTRODUCTION

Any model where electroweak symmetry is broken by a Higgs field faces the challenge of explaining why the weak scale is so much lower than the Planck scale, the `hierarchy problem'.

The hierarchy problem arises because the Higgs mass parameter receives quadratically divergent radiative corrections from the gauge interactions, Yukawa interactions and Higgs self-couplings.



In order to generate the hierarchy between the weak scale and the Planck scale, these radiative corrections must be fine-tuned against the bare Higgs mass parameter to more than thirty orders of magnitude.

Any solution to the hierarchy problem requires new physics at or close to the weak scale that couples to the Standard Model fields with order one strength. However, precision electroweak measurements tightly constrain any such new physics, leading to the problem known as the LEP paradox.

To understand the LEP paradox, let us go back to the fine-tuning problem of the Standard Model.

The Higgs potential in the Standard Model takes the following form.

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

Minimizing this potential we find for the electroweak VEV

$$v^2 = m^2/2\lambda$$

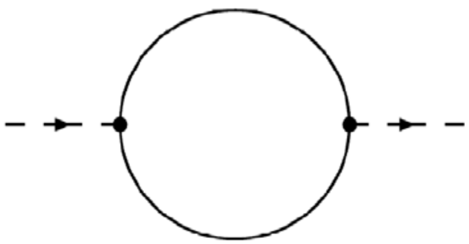
and for the mass of the physical Higgs

$$m_H^2 = 4\lambda v^2 = 2m^2$$

We can estimate the fine-tuning as $\delta m^2/m^2$ where δm^2

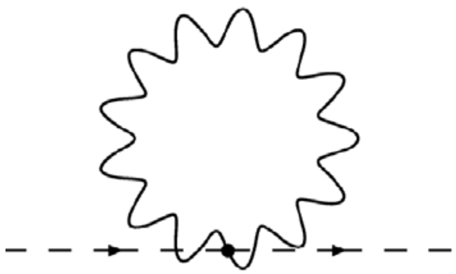
is the radiative correction to the mass squared parameter.

For a physical Higgs mass of 200 GeV, the precision electroweak upper bound, we can estimate the fine-tuning from the top, gauge and Higgs self couplings.



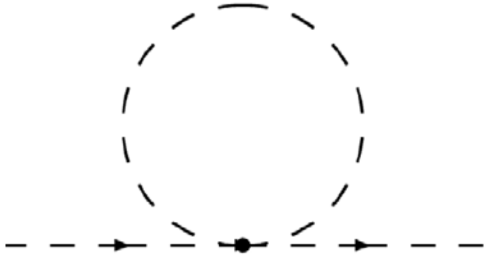
$$= \frac{3y_t^2}{8\pi^2}\Lambda^2$$

Fine Tuning < 10% for Λ > 2 TeV.



$$= \frac{9g^2}{64\pi^2}\Lambda^2$$

Fine Tuning < 10% for Λ > 6 TeV.



$$= \frac{3\lambda}{8\pi^2}\Lambda^2$$

Fine tuning < 10% for Λ > 5 TeV.

We see that unless the Standard Model is severely fine-tuned, we should expect new physics at or close to a TeV.

At the same time, we expect that any new physics which addresses the hierarchy problem will couple to the Standard Model fields with (at least) order one strength. In general, when these new states are integrated out, they will generate operators like those below, which contribute to precision electroweak observables.

$$\frac{D^2 H \overline{D}^2 H^\dagger}{\Lambda^2} \qquad \frac{|H^\dagger D_\mu H|^2}{\Lambda^2}$$

Here Λ is of order the mass of the new states, which the preceding fine-tuning arguments tell us must be near the TeV scale.

The problem arises because measurements at LEP have already constrained the scale Λ which appears in these operators to be greater than 5 TeV. This is the LEP paradox, or `little hierarchy problem'.

The LEP paradox leaves us with three distinct possibilities.

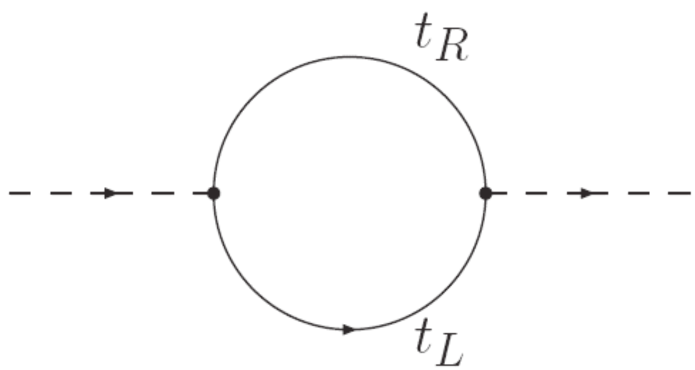
- **There is no new physics which stabilizes the weak scale below 5 TeV. In this case the Higgs mass is simply fine-tuned at the 2% level or worse.**

- **There is new physics below 5 TeV which stabilizes the weak scale, and which contributes significantly to precision electroweak observables. Consistency with precision electroweak data is a consequence of accidental cancellations between different contributions. In this case the agreement of the Standard Model with the data is merely a coincidence.**

- **There is new physics below 5 TeV which stabilizes the weak scale, but does not contribute significantly to precision electroweak observables. This can happen if, for example, the relevant operators are not generated at tree level, but only at loop order, as in supersymmetry.**

Since the LHC is not expected to be able to probe scales significantly higher than 5 TeV, the most pragmatic approach is to search for new models which fall into the third category. This is a powerful restriction on possible models. One such class of theories is folded supersymmetry.

The biggest contribution to the Higgs mass in the Standard Model is from the top loop, and this is therefore the leading source of fine-tuning.



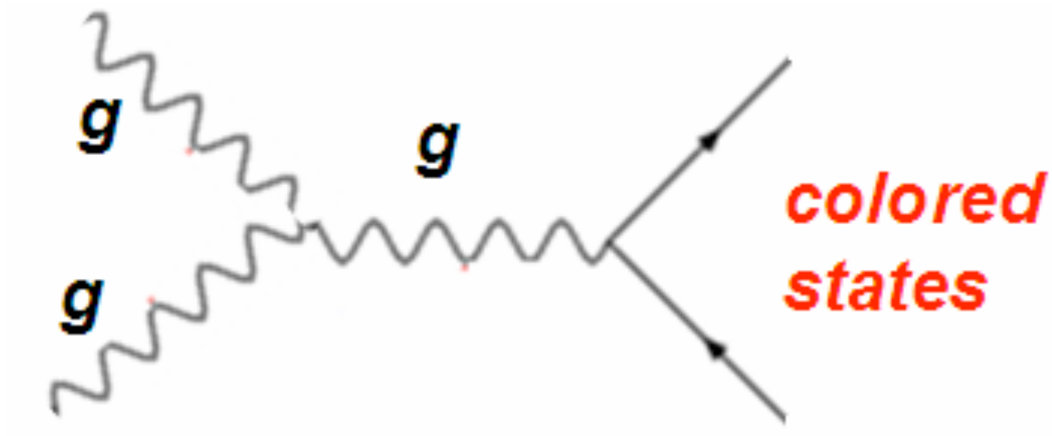
$$\sim \frac{3{\lambda_t}^2}{8\pi^2}\,\Lambda^2$$

Naturalness requires new particles below a TeV or so to cancel this.

FOLK THEOREM:

The new particles must be related to the top quark by a symmetry for the cancellation to go through. Since the top quark is colored, these new states, the `top partners’, will also be colored.

This folk theorem has crucial implications for the LHC. Why? The LHC is a hadron machine and has therefore far more reach for colored states than for color singlets.

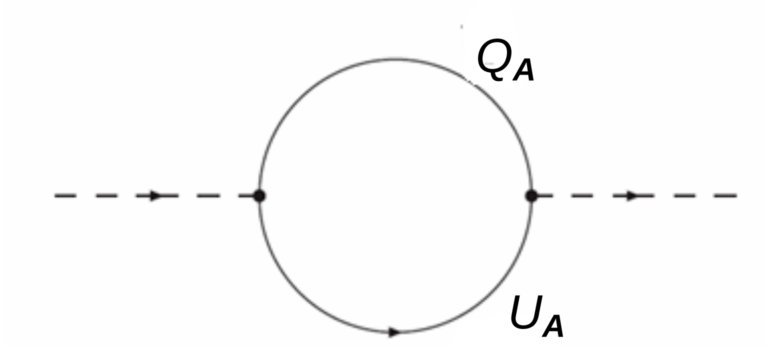


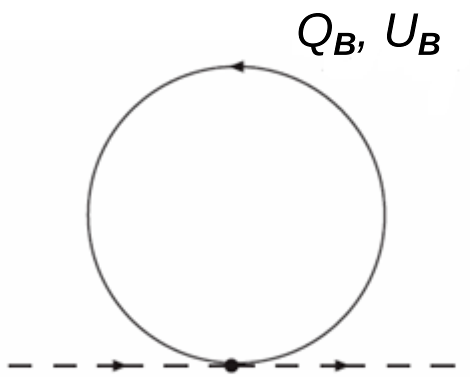
If the top partners are colored, the odds are good that the LHC will find them. If not, it is not clear that the LHC will find new physics. The folk theorem is good news!

However, . . .

The folk theorem is wrong. An explicit counter-example, the mirror twin Higgs model exists. (Z.C., Goh & Harnik)

The cancellation of the top loop takes pace through a diagram of exactly the same form as in the (simplest) little Higgs case. The major difference is that the fermions running in the loop, the top partners, are now mirror quarks, which are not charged under Standard Model color.





The crucial point to appreciate is that in this cancellation, color is simply a multiplicative factor of 3 with no further significance! What really matters is that the vertices in the two diagrams be related in a specific way by symmetry.

In light of this, let us re-examine the cancellation of the top loop in SUSY.

Here again, the fact that the scalars running in the loop are colored does not seem crucial to the cancellation, any more than in the little Higgs case. As before, color seems to serve merely as a multiplicity factor, with no further significance. What matters is that the vertices in the two diagrams be related in a specific way by symmetry.

This observation begs the following question. Do there exist theories where the cancellation of the top loop takes exactly the same form as in the SUSY case but where the states running in the loop are scalars not charged under Standard Model color ?

FOLDED SUPERSYMMETRY

Such theories do exist. They constitute examples of `folded supersymmetric' models.

Folded supersymmetric theories are built around the following observation.

In the large *N* limit a relation exists between the correlation functions of supersymmetric theories and those of their non-supersymmetric orbifold daughters that holds to all orders in perturbation theory. The masses of scalars in the daughter theory are protected against quadratic divergences by the supersymmetry of the mother theory.

Kachru & Silverstein,
Lawrence, Nekrasov & Vafa,
Bershadsky, Kakushadze & Vafa,
Kakaushadze,
Bershadsky & Johansen,
Schmaltz.

In most cases, at one loop, the cancellations go through approximately even at small *N.* By identifying the structure underlying the cancellation of one loop quadratic divergences in these theories we can construct new classes of models which address the LEP paradox.

Based on this observation, we outline a set of procedures which suitably extend the particle content and vertices of a theory so as to cancel the one loop quadratically divergent contribution to the mass of a scalar arising from a specific interaction, to leading order in *N*. These `rules' apply to Yukawa interactions and also to SU(N) gauge interactions.

- **Supersymmetrize.**

- **In the relevant graphs identify an index as being summed from 1 to *N.* By suitably expanding the particle content and gauge, global and discrete symmetries of the theory, extend this sum from 1 to 2*N*. For Yukawa interactions and gauge interactions this can always be done in such a way that the resulting theory is invariant under $Z_{2\Gamma}$ and Z_{2R} symmetries.**

- **Project out states odd under the combined $Z_{2\Gamma}$ and Z_{2R} symmetries. The resulting daughter theory will be free of quadratic divergences to leading order in *N*.**

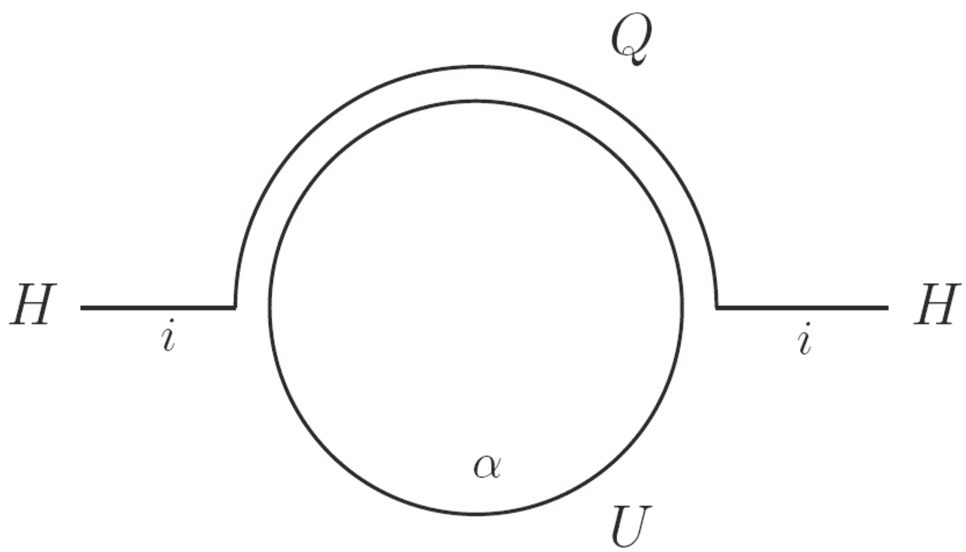
When applied to SU(N) gauge interactions, and to Yukawa interactions, an ultraviolet completion can always be found for the daughter theory that enforces this cancellation.

We now apply these ideas to the construction of a model where the top loop is cancelled by scalars not charged under color.

In supersymmetric models the top Yukawa coupling has the form below in the superpotential.

$$\lambda_t\, (3,2)_{Q_3}\, (1,2)_{H_U}\, \left(\overline{3},1\right)_{U_3}$$

Here Q_3 represents the third generation SU(2) doublet containing the top and bottom quarks, H_U the up-type Higgs and U_3 the third generation SU(2) singlet (anti) top quark. If we treat both SU(2) indices *i* and SU(3) indices α as large *N* indices, then in t'Hooft double line notation the relevant diagram takes the form shown on the next slide.



It is clear from the figure that it is the SU(3) indices α that are being summed over in the loop. This sum can be doubled in either of two ways.

- Extend the gauge symmetry from SU(3) to SU(6).

- Extend the gauge symmetry from SU(3) to [SU(3) X SU(3)], with a discrete symmetry interchanging the two SU(3) groups.

We will follow the second approach for the rest of this talk.

The top Yukawa interaction in the `mother theory' then takes the form

$$\lambda_t \left[Q_{3A} H_U U_{3A} + Q_{3B} H_U U_{3B} \right]$$

where Q_{3A} and U_{3A} are the familiar third generation quarks of the Standard Model, while Q_{3B} and U_{3B} are charged under a mirror color gauge group. Note that Q_{3B} and U_{3B} still carry SU(2) and U(1) quantum numbers.

The theory possesses a $Z_{2\Gamma}$ symmetry under which Q_{3A} and U_{3A} are odd while Q_{3B} and U_{3B} are even. H_U and the vector superfields are also all even under $Z_{2\Gamma}$.

The theory is also invariant under a discrete Z_{2R} symmetry under which all fermionic fields are odd and all bosonic fields even.

Under the combined $Z_{2\Gamma}$ X Z_{2R} symmetry the fermions in Q_{3A} and U_{3A} are even while the bosons are odd. Correspondingly bosons in Q_{3B} and U_{3B} are even and fermions odd. All gauge bosons are even and all gauginos odd.

After projecting out the odd states let us consider quadratically divergent contributions to the mass parameter of the up-type Higgs field. The relevant interactions have the form below. Here α and β are color and mirror color indices respectively.

$$\left[\, \lambda_t\, h_u\, q_\alpha\, u_\alpha \;+\; \mathrm{h.c.} \,\right] \;+$$
$$\lambda_t^2\, |\tilde{q}_\beta h_u|^2 + \lambda_t^2\, |\tilde{u}_\beta|^2\, |h_u|^2$$

The one loop quadratic divergences from fermion loops cancel against those from scalar loops just as in supersymmetric theories. However, the scalar fields responsible for this cancellation are not charged under Standard Model color, but under a different, hidden color group.

However, the equality of various couplings necessary for this cancellation does not follow from any symmetry principle. This must emerge as an initial condition from ultra-violet physics.

A consistent way to do this is to begin with a supersymmetric theory in five dimensions and use the Scherk-Schwarz mechanism to project out the zero modes of the odd fields.

$y = 0$ $\qquad\qquad$ $y = \pi R$

$SU(3)_A$, $SU(3)_B$, $SU(2)_L$ and $U(1)_Y$

$$\hat{Q}_{iA},\ \hat{U}_{iA},\ \hat{D}_{iA},\ \hat{L}_{iA} \text{ and } \hat{E}_{iA}$$

$$\hat{Q}_{iB},\ \hat{U}_{iB},\ \hat{D}_{iB},\ \hat{L}_{iB} \text{ and } \hat{E}_{iB}$$

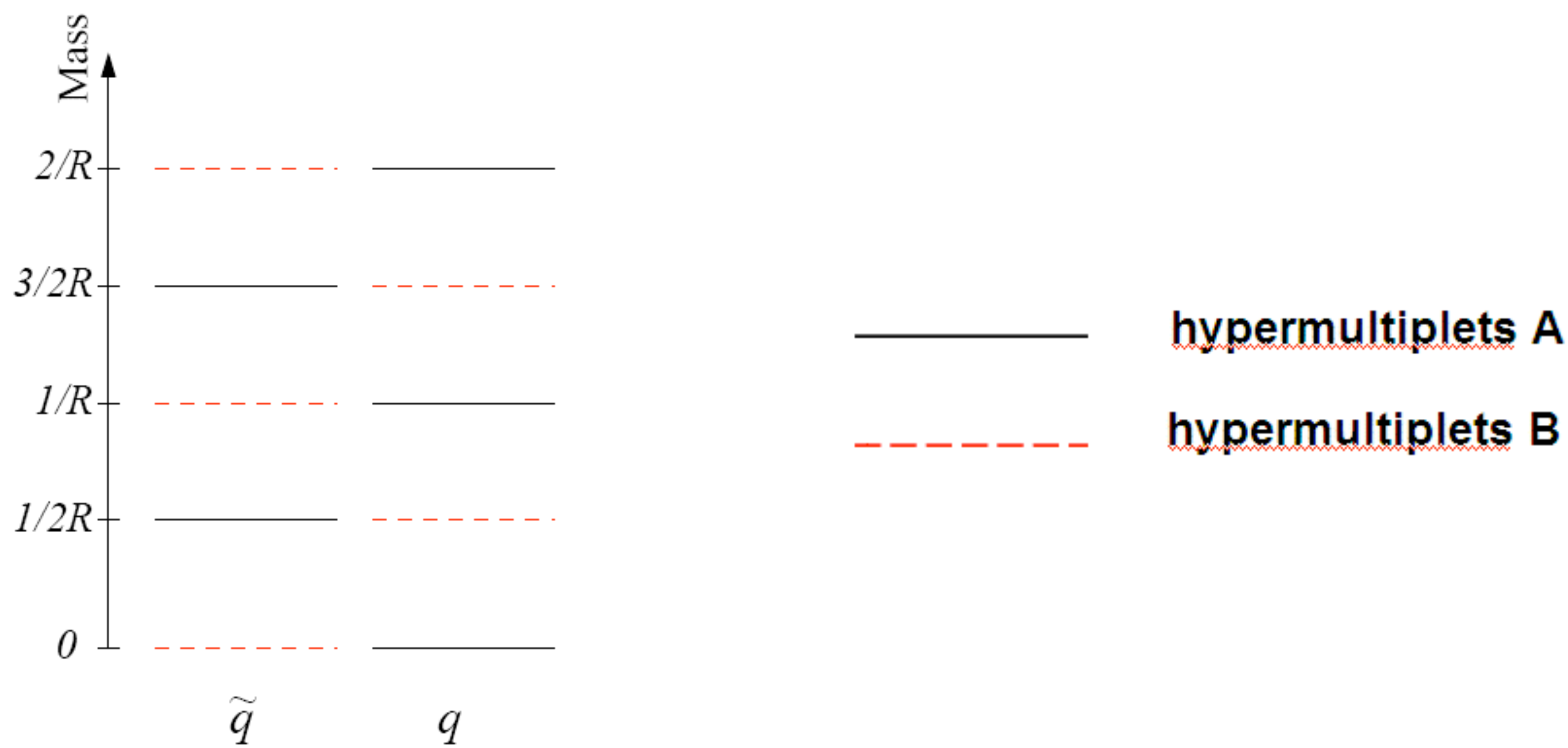
H_U , H_D

The boundary conditions on the bulk fields are chosen to break SUSY by the Scherk-Schwarz mechanism in such a way that each Standard Model hypermultiplet (labelled by *A*) has a fermionic zero mode while the B hypermultiplets each have a bosonic zero mode. In this way the Standard Model fermions and their corresponding bosonic`folded superpartners' are kept light while all the other modes are heavy.

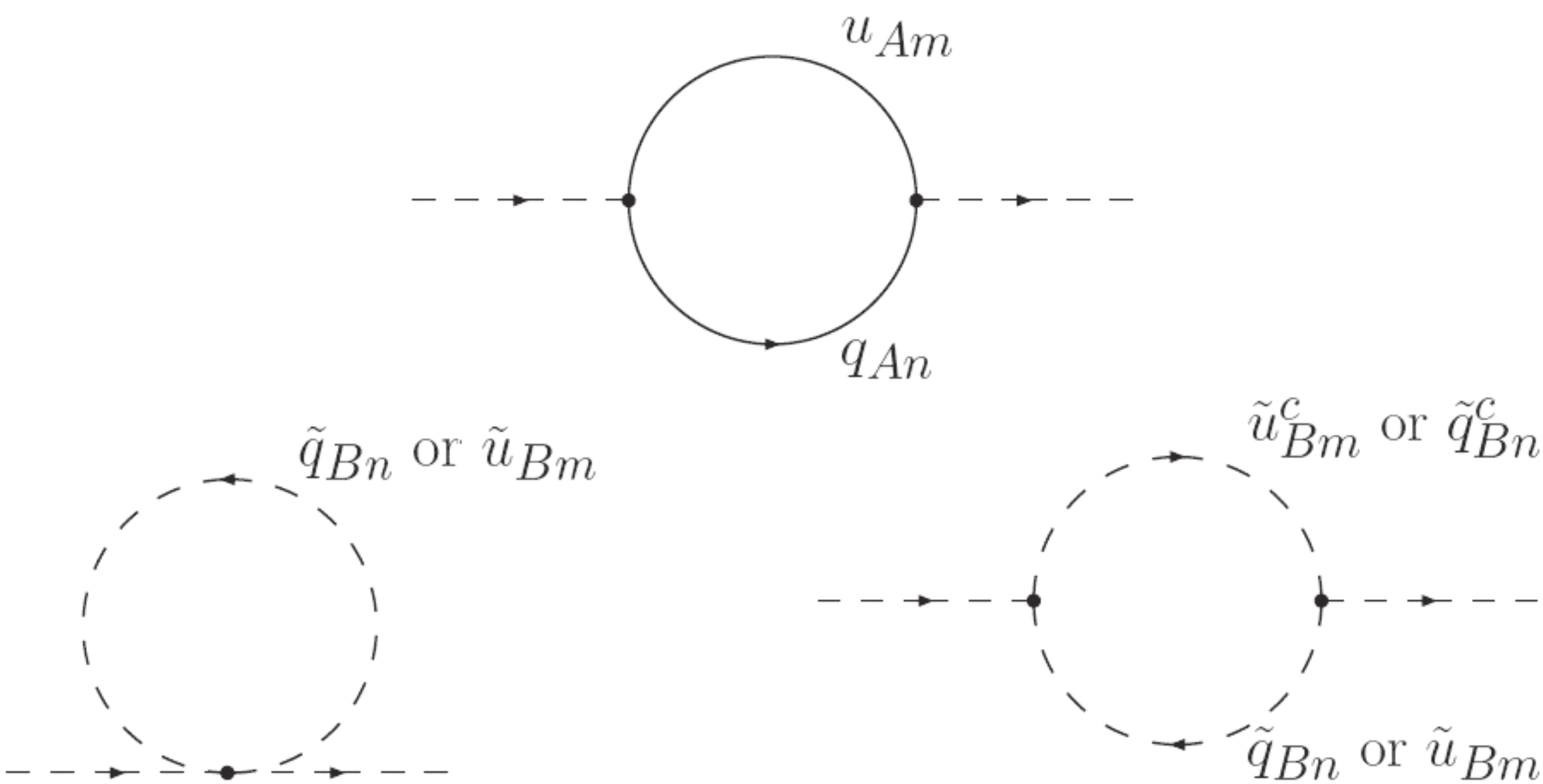
Similarly the boundary conditions are such that all gauge fields have zero modes while the corresponding gauginos are massive.

By construction, the zero modes have exactly the right quantum numbers to cancel the top loop. But what about corrections from the Kaluza-Klein tower?

It turns out that these contributions do in fact cancel. The reason is that there are equal numbers of bosonic and fermionic states at every level of the Kaluza-Klein tower, and these couple to the Higgs with exactly the right strength to guarantee cancellation.



The relevant diagrams have the form below.



QUIRKY COLLIDER SIGNATURES

A characteristic feature of this theory is the existence of scalar `quirks' that cancel the top loop.

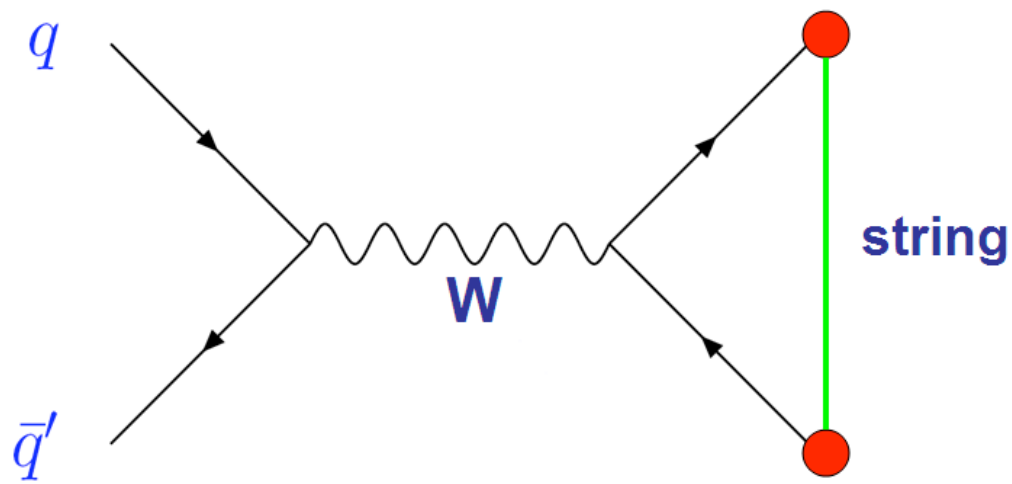
Quirks are particles that transform under a hidden, confining gauge group, but which also carry Standard Model gauge charges. By assumption, the confinement scale of the hidden group Λ is lower than the mass M of the quirks . For folded supersymmetry $\Lambda \sim 5 - 10$ GeV, while M ~ 100 – 800 GeV.

Okun,
Gupta & Quinn,
Strassler & Zurek,
Luty & Kang

The presence of quirks in folded supersymmetric theories leads to unusual and characteristic collider signatures that are fundamentally different from other solutions of the LEP paradox.

What's unusual about quirks?

Consider a quirk and anti-quirk that are pair-produced at a collider. The crucial observation is that the two quirks cannot hadronize separately, because there are no light particles that transform as the fundamental of the confining group. Instead, at distances larger than Λ the two quirks remain connected by a string of hidden color.



Since the initial kinetic energy of the quirks is in general much larger than the confinement scale, the string can be very long, even macroscopic! Eventually the string pulls the quirks back together and they annihilate into Standard Model particles. Gives rise to striking collider signatures!

What parameters does quirk phenomenology depend on?

- **The quirk mass M.**
- **The scale Λ at which the confining group gets strong.**
- **The Standard Model (SM) quantum numbers of the quirks. `Colorful' quirks carry SM color. `Colorless' quirks don't.**
- **Scalars or Fermions.**

Fermionic quirks cannot couple directly at the renormalizable level to Standard Model fermions. Couplings to the Higgs require two or more quirks with different quantum numbers.

However scalar quirks can couple at the renormalizable level to the Higgs.

$$|H|^2|\tilde{Q}|^2$$

In a folded supersymmetric model it is this term that cancels the contribution to the Higgs mass parameter from the top loop. Such a term can also have phenomenological consequences.

Anatomy of an Event

Any collider event involving quirks occurs in three stages.

- production
- annihilation
- energy loss

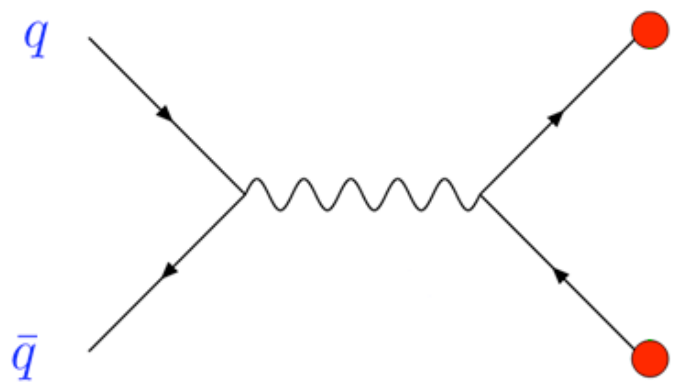
In the first stage the quirks are pair-produced through an off-shell gluon, W, Z or photon.

The quirks are initially produced with considerable kinetic energy. In the second stage, as the string pulls the quirks together, this energy is lost to hidden sector glueballs, photons, and Standard Model hadrons. For long strings, energy loss in the detector must also be accounted for.

In the final stage, the quirks pair-annihilate back into Standard Model particles, or into hidden sector states.

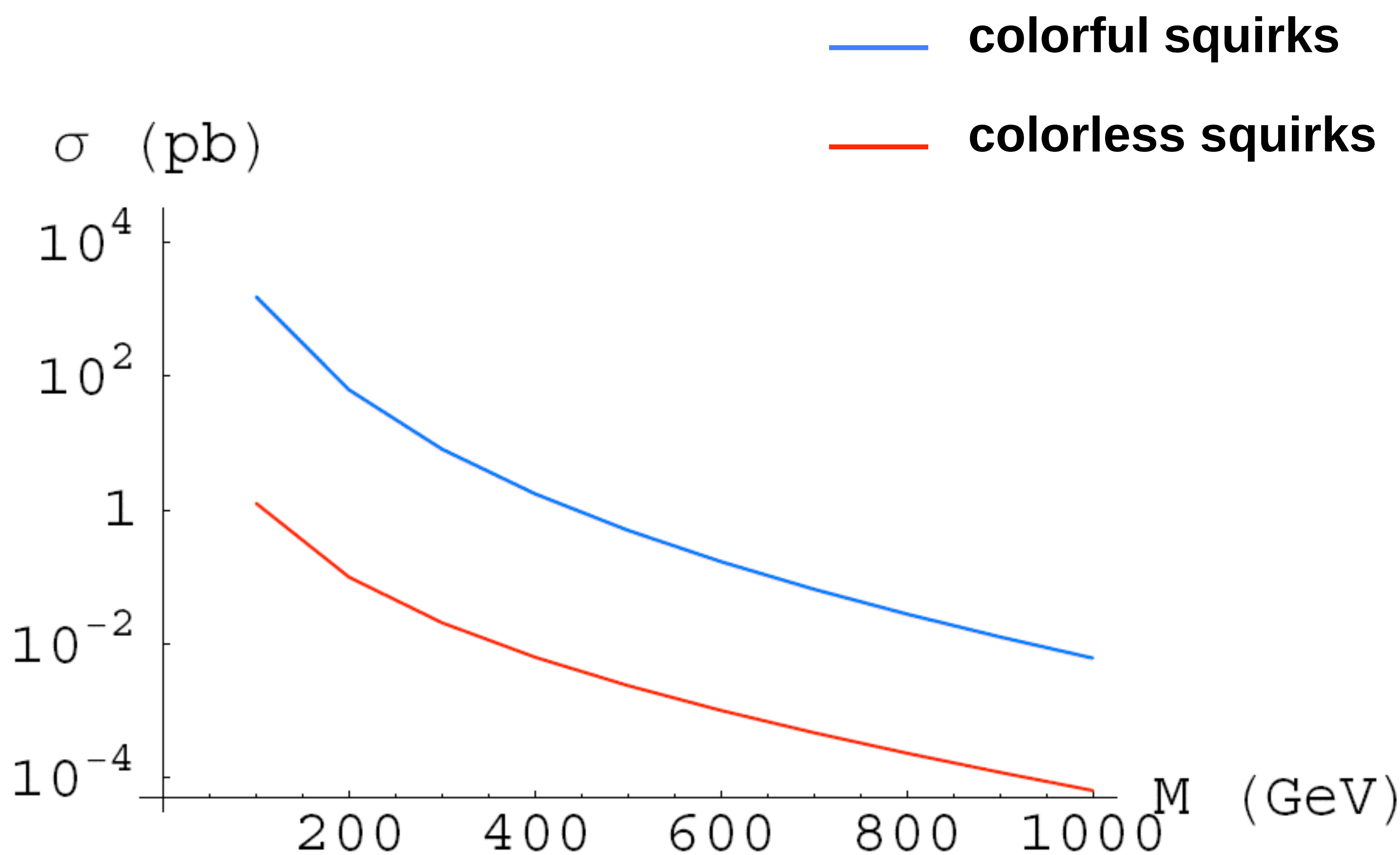
Production

The quirks are pair-produced in the s-channel through an off-shell gluon, W, Z or photon. The rate depends on the Standard Model quantum numbers of the quirks and is straightforward to calculate. The confining group only determines a trivial multiplicity factor.



If the quirks are charged under Standard Model color, at the LHC production through the gluon dominates.

For colorless quirks, the case relevant to folded supersymmetry, the main production channel is through an off-shell W. This has the advantage that annihilation into purely invisible states is forbidden, due to electric charge conservation. While production through Z and photon is also significant, in these cases annihilation is almost entirely to hidden glueballs.


colorful squirks
colorless squirks
σ (pb)
10^4
10^2
1
10^-2
10^-4
M (GeV)
200
400
600
800
1000

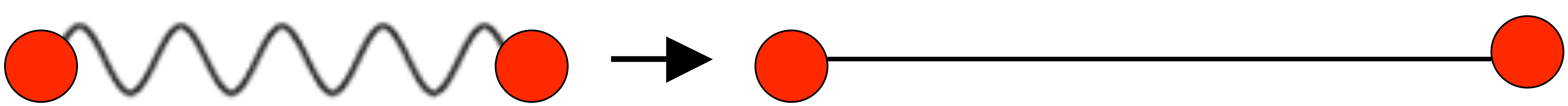
Quirk Energy Loss

What can quirks lose energy to?

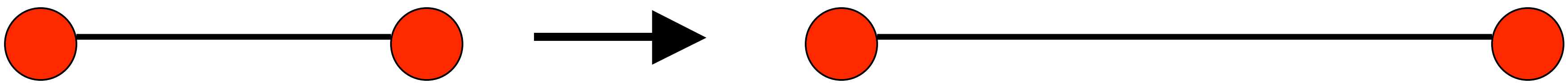
- photons
- glueballs of the confining group
- Standard Model hadrons (if the quirks are colored)
- the detector (if the string is long enough)

Let us understand how this happens, semi-classically.

Once the quirks are separated by a distance much more than $1/\Lambda$, a string forms between them. The lowest energy configuration of the string corresponds to when it is straight. As the quirks separate, the string gets straightened out.



As the quirks move further apart, the length of the string grows, and it remains approximately straight. During this period, because of the glueball mass gap, we don't expect significant energy loss to glueballs. Also, locally there is no lower energy configuration for the string to de-excite to.



The string has a tension $T \sim \Lambda^2$, which causes the two quirks to decelerate, and eventually come to rest. The string length L is then of order E/Λ^2 , where E is the initial kinetic energy of the quirks.

For E ~ 100 GeV, and

- $\Lambda \sim 1$ KeV, L ~ 10 mm → displaced vertex
- $\Lambda \sim 100$ eV, L ~ 1m → quirks enter detector → energy loss

However, in the case of folded supersymmetry, $\Lambda \sim 5$ -10 GeV, L < fm and these effects are absent.

The acceleration of the quirks caused by the string tension causes them to radiate photons. The photon frequency is of order Λ^2/M. This is the origin of the photon energy loss.

Once maximum separation has been reached, the string tension causes the quirks to move back towards each other. Since the net angular momentum of the system is small, of order a few, the impact parameter is of order $1/M$. Since this is smaller than $1/\Lambda$, we expect some energy loss to hidden sector glueballs when the quirks cross. If the quirks carry Standard Model color, there will also be energy loss to hadrons.

The number of oscillations the quirks perform before annihilating depends on the efficiency of these energy-loss mechanisms. If inefficient, we expect displaced vertices and tracks in the detector even for larger values of Λ. The quirks may also annihilate before losing all their energy.

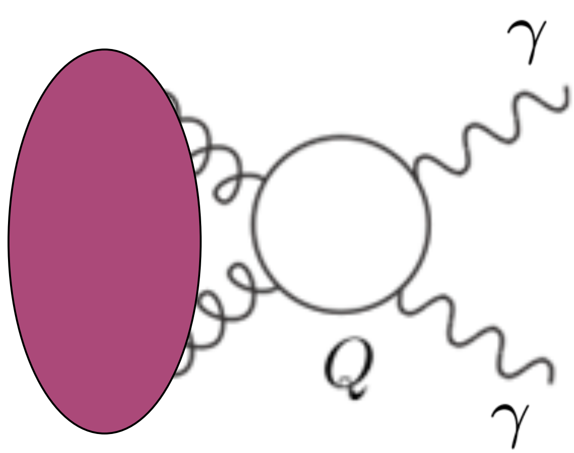
In the case of folded supersymmetry, annihillation is prompt on collider timescales, and there are no displaced vertices. We assume that the squirks lose most of their energy before annihillating.

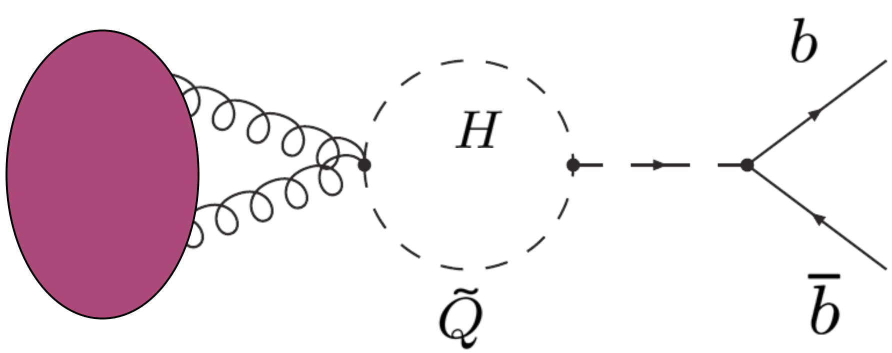
Can hidden glueballs be detected?

It is possible to detect hidden glueballs if they decay inside the detector. In the case of colorless quirks, the dominant decay channel is to photons, through a loop of virtual quirks. For colorful quirks, for values of Λ greater than a few GeV, decays to hadrons are preferred. These decays will happen in the detector for Λ > 20 GeV.

In the case of scalar quirks, because of the renormalizable couplings to the Higgs, decays to Standard Model fermions may be preferred. For Λ > 20 GeV, these are to b's.

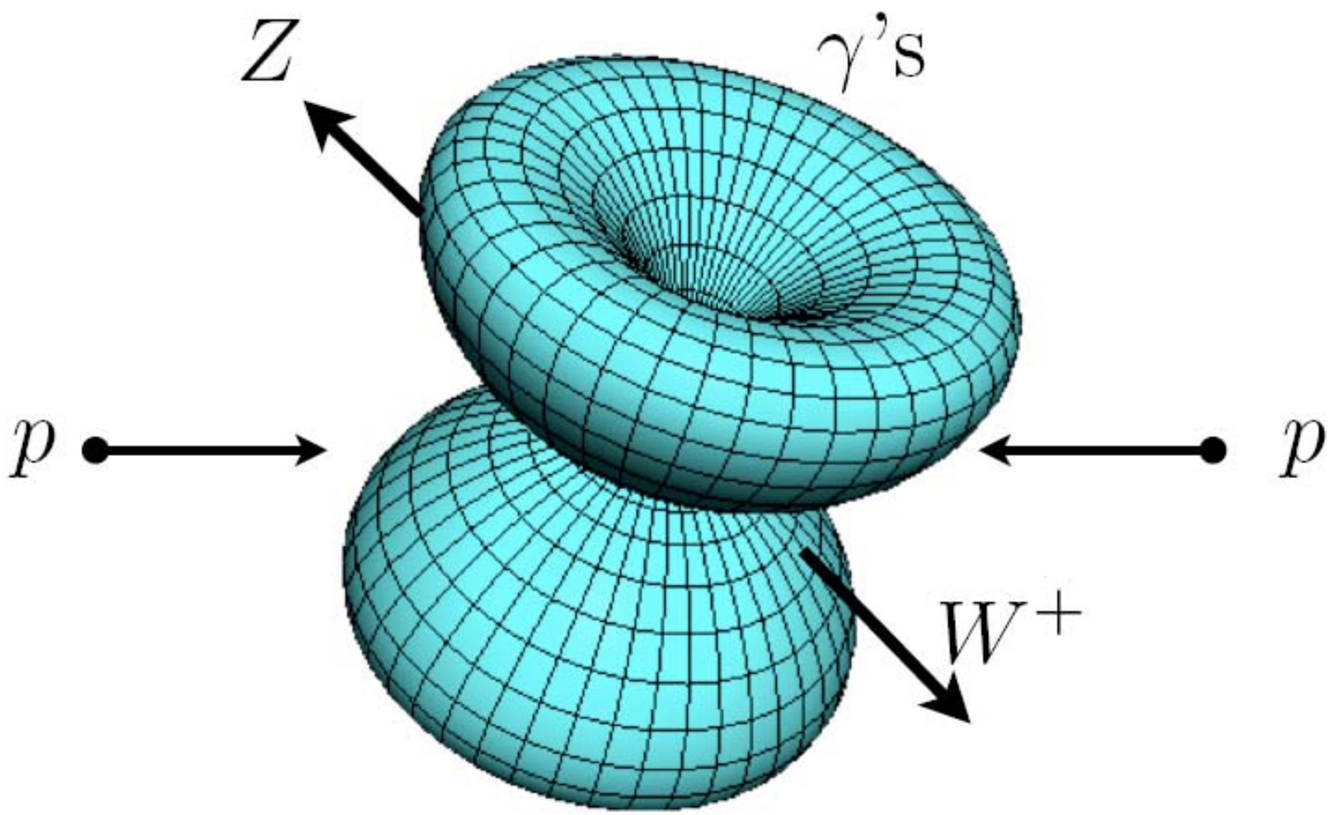
In the case of folded supersymmetry, we expect most decays will occur outside the detector.





Can the soft photons be detected?

For Λ ~ 10 GeV the soft photons have frequencies of order 100 MeV to 1 GeV, and have a characteristic angular distribution. They may be possible to detect, after triggering on the annihilation products. (Harnik & Wizansky)



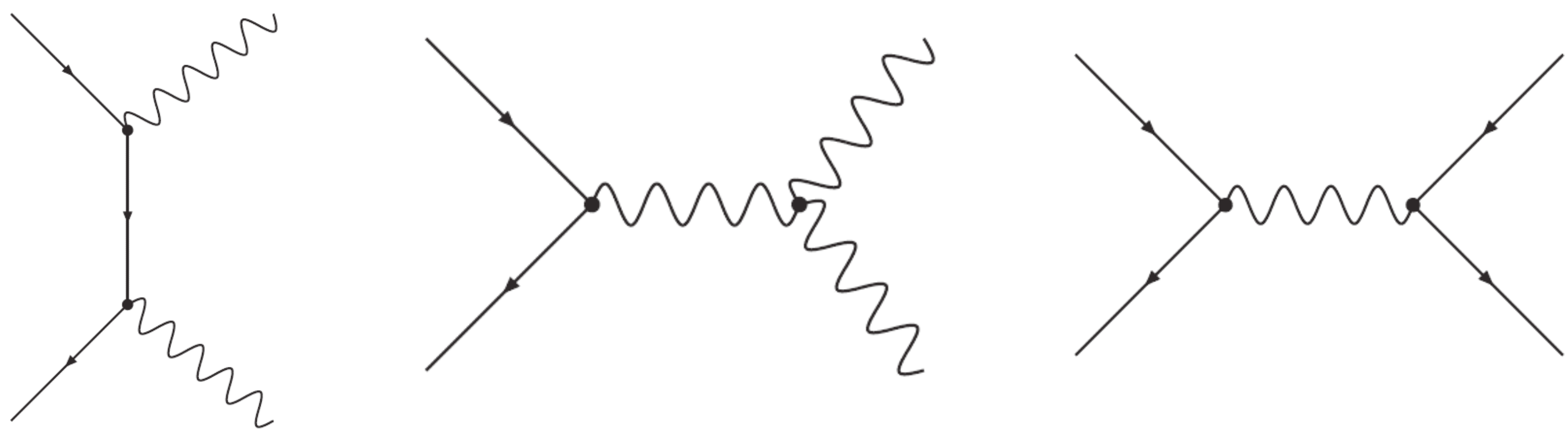
Quirk Annihilation

For quirks pair-produced through a W, the leading annihilation channels are

- W + Z, either through the exchange of a t-channel quirk or an s-channel W

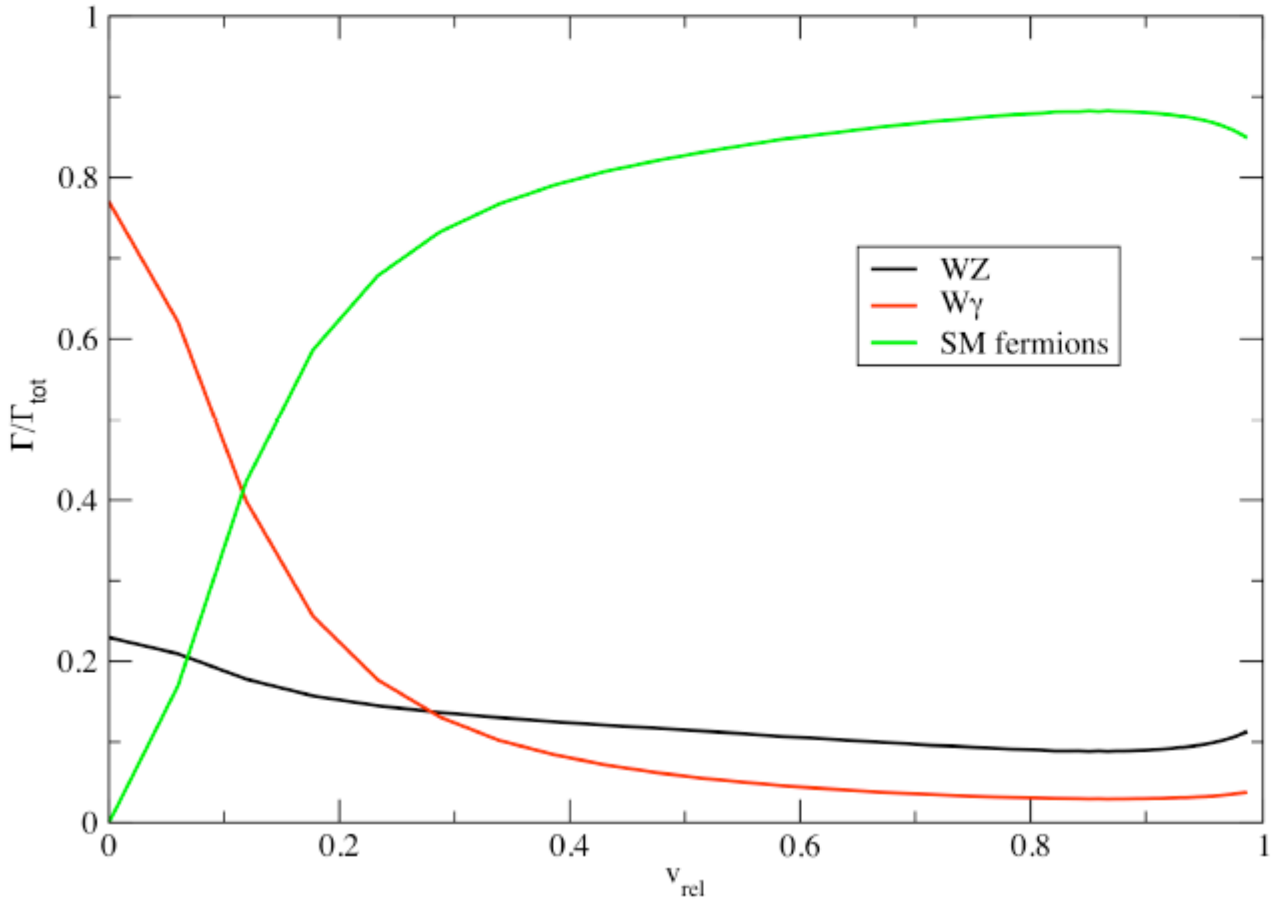
- W + photon, through exactly the same channels

- two Standard Model fermions, through an s-channel W



For scalar quirks, there is an additional diagram that contributes to W + Z and W + photon, corresponding to the four point vertex.

The collider signals of folded supersymmetry depend on the branching ratios of squirk-antisquirk pairs into the various final states. For low relative velocity, corresponding to efficient energy loss, W + photon dominates.



The branching ratios in the fermionic quirk case are completely different.

Assuming efficient energy loss, we expect a peak in W + photon at an energy corresponding to twice the squirk mass. However, if energy is radiated in glueballs, the squirk pairs will have momentum transverse to the beam axis when they annihilate of order √(ΛM) . This means that if we look for leptonic decay channels of the W the peak will be smeared out by about this amount.

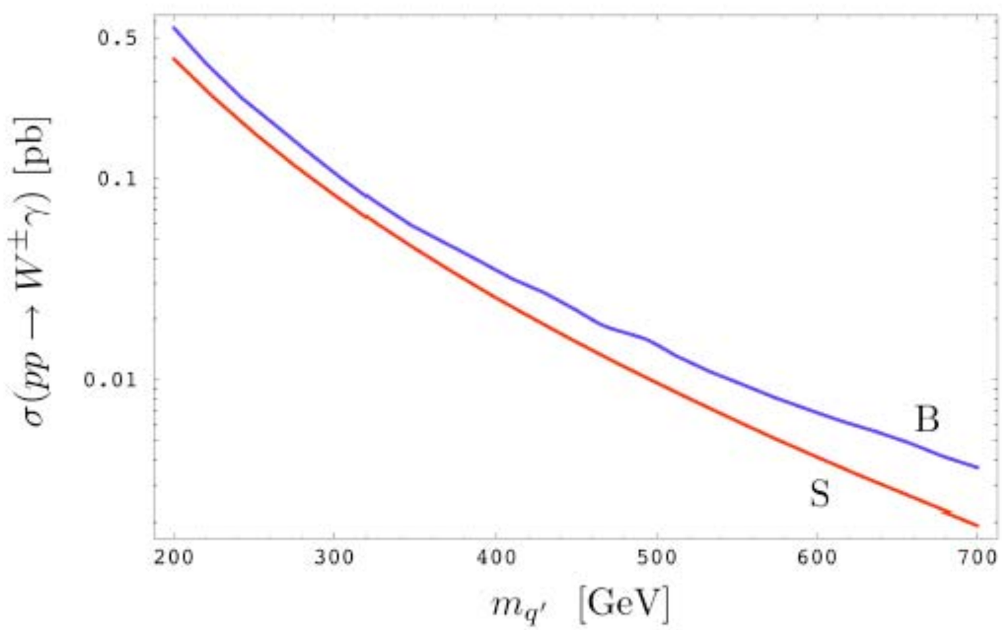
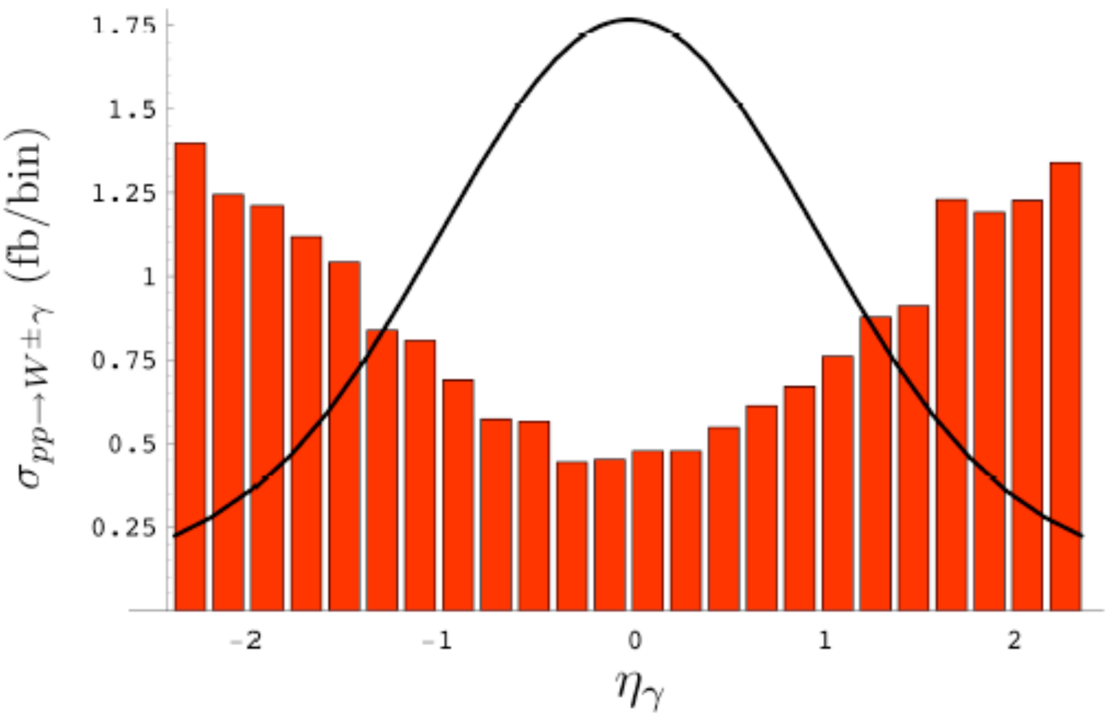


FIG. 3: An estimate of the signal versus the background as a function of the squirk mass in GeV. The bottom curve is the squirk pair production cross section in the charged channel. The annihilation of these squirk pair will dominantly produce $W^{\pm}$+photon with and invariant mass of $\sim 2m_{q'}$. The top curve is the SM $W^{\pm}$+photon with $|m_{W\gamma} - 2m_{q'}| < \sqrt{\Lambda m_{q'}}$ for $\Lambda = 15$ GeV.

Assuming the branching fraction for squirkonium decays to W + photon is of order 0.6, and limiting the analysis to leptonic decays of the W, we find that a 5σ discovery of 400 GeV squirks is possible at the LHC with 11 inverse fb of data. This can be improved further with a pseudo-rapidity cut.



By making a cut on pseudo-rapidity of $|\eta| < 1.5$, we can reduce the signal to background by a factor of more than two. Then 5σ discovery of 400 GeV squirks is possible with 8.5 inverse fb. With 100 inverse fb, squirks with mass up to 650 GeV can be discovered.

Conclusions

In folded supersymmetric theories the top loop is cancelled by scalar quirks with no charge under Standard Model color.

These particles can be pair-produced through an off-shell W. Assuming efficient energy loss, the dominant annihilation channel is to W + photon.

The signal is a (smeared) peak in the energy distribution of W + photon. By probing leptonic decay channels of the W, and after suitable cuts, discovery of 400 GeV squirks is possible with about 10 inverse fb of data. With 100 inverse fb this improves to about 650 GeV.